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Implications of the muon anomalous magnetic moment and Higgs-mediated flavor changing neutral currents

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Abstract

In the light of the recent measurement of the muon anmalous magnetic moment a_μ by the Muon $(g-2)$ Collaboration, we examine the contribution to a_μ from the exchange of flavor changing scalars. Assuming that the heavier generations have larger flavor changing couplings, we obtain a bound on $\mu - \tau$ Yukawa coupling for a given scalar mass. Constraints on other flavor changing/conserving couplings are also obtained from the lepton flavor violating decays of muon and tau lepton, and bounds on the branching ratio of $\tau \to 3e$, $\mu \to 3e$ and $\tau \to e\mu e$ processes are predicted.

Very recently, the Muon $(g-2)$ Collaboration has reported a measurement of the anomalous magnetic moment of the muon, indicating a 2.6σ deviation of $a_\mu \equiv (g_\mu - 2)/2$ from the standard model (SM) prediction [1]:

$$\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM} = (426 \pm 165) \times 10^{-11}. \tag{1}$$

Although the measurement of a_μ is about 350 times less precise than that of a_e, it is much more sensitive to new physics effects since such contributions are generally proportional to m_l^2 [2,3]. In this spirit, the deviation exhibited in Eq. (1) may be regarded as a signal of new physics beyond the SM, and at 90% C.L., Δa_μ^{NP} must lie in the range

$$215 \times 10^{-11} \lesssim \Delta a_\mu^{NP} \lesssim 637 \times 10^{-11}. \tag{2}$$

Various proposals of new physics have been suggested to accommodate this deviation, and it has also been employed to constrain the unknown parameters [4].

In this paper, we will examine another possibility that stems from Higgs-mediated lepton flavor violating neutral interactions which contribute to the anomalous magnetic moment of the muon. In general the flavor changing neutral current (FCNC) interactions can be generated at tree level in the two-Higgs doublet extension of the SM. Since such tree level flavor changing neutral current interactions are phenomenologically dangerous, one usually impose a discrete symmetry in order to avoid the FCNC problem. However, no tree level FCNC may not be necessary, alternatively one can consider the very general model with extended Higgs sector where the flavor changing neutral couplings are just constrained by experiments. Nie and Sher have studied the effects of those Higgs-mediated FCNC couplings on a_μ, and shown that contribution from the exchange of flavor-changing scalars can be enhanced as long as the mass of scalar is light enough [5]. Reliably assuming that the heavier generations have larger flavor changing couplings [6], they have obtained a bound on $\mu - \tau$ Yukawa coupling from the measured value of a_μ. In this work, we will re-analyze the effects of the lepton flavor changing (particularly $\mu - \tau$) coupling on a_μ to obtain an improved bound on the coupling in the light of new measurement of a_μ. On the other hand, such FCNC couplings generically lead to the lepton flavor violating decays of τ and μ which should be strongly constrained by experimental data. Combining the constraint on the coupling obtained from Eq.(2) with experimental limits on the branching ratios of the corresponding processes, it is possible to estimate bounds on other flavor changing/conserving couplings, $e-e$, $e-\mu$, $e-\tau$, $\mu-\mu$, and $\tau-\tau$. We will investigate the bounds on those couplings and the branching ratios for lepton flavor violating three-body decays of τ.

Following Ref. [5], we choose a basis for the two Higgs doublets, H and Φ, such that only one Higgs doublet, H, obtains a vacuum expectation value. After the rotation of the charged leptons, corresponding neutral Higgs boson H^0 has flavor-diagonal couplings, while the other neutral Higgs boson, ϕ, have flavor changing couplings. The relevant terms for Yukawa interaction in the Lagrangian are then given by [5]

$$L = \frac{\sqrt{2}}{v}\left(m_e \overline{e}_L e_R H^0 + m_\mu \overline{\mu}_L \mu_R H^0 + m_\tau \overline{\tau}_L \tau_R H^0\right) + h_{ij} \bar{l}_{iL} l_{jR} \phi + H.c. \tag{3}$$

where $\langle H \rangle = (0, v/\sqrt{2})^T$, and the ϕ field consists of a scalar ϕ_s and a pseudoscalar ϕ_p. The lepton flavor changing couplings can induce new contributions to the anomalous magnetic

moment of the muon, a_μ, as well as the lepton flavor violating decays of the muon and tau through scalar and pseudoscalar-mediated diagrams. As shown in Ref. [6], the heavier generations are naturally expected to have larger flavor-changing couplings. Then, the most dominant contributions to the anomalous magnetic moment of the muon arise from $h_{\mu\tau}$ coupling. The scalar and pseudoscalar contributions to a_μ are given by [5]

$$a_\mu^{s,p} = \frac{h_{\mu\tau}^2 m_\mu^2}{16\pi^2} \int_0^1 dx \frac{x^2 - x^3 \pm (m_\tau/m_\mu)x^2}{m_\mu^2 x^2 + (m_\tau^2 - m_\mu^2)x + m_{\phi_{s,p}}^2 (1-x)}, \tag{4}$$

where $m_{\phi_{s,p}}$ is the mass of the scalar or pseudoscalar, and the $+(-)$ sign corresponds to the scalar (pseudoscalar). In the limit $m_\mu \ll m_\tau \ll m_\phi$, the leading term becomes

$$a_\mu \simeq (\pm) \frac{h_{\mu\tau}^2}{16\pi^2} \frac{m_\mu m_\tau}{m_\phi^2} \left(\ln \frac{m_\phi^2}{m_\tau^2} - \frac{3}{2} \right). \tag{5}$$

We note that the scalar exchange yields a positive contribution to a_μ, while the pseudoscalar exchange leads to a negative one. Since our goal is to explain the recent measured value of a_μ which indicates a positive value of Δa_μ, we demand that the contribution from the scalar exchange dominates over that from the pseudoscalar exchange. This can be easily achieved by assuming that the pseudoscalar is sufficiently heavier than the scalar. We see from Eq.(5) that a_μ decreases as the mass of the scalar increases for a fixed $h_{\mu\tau}$. For a given m_ϕ, Δa_μ yields a constraint on the coupling $h_{\mu\tau}$. In particular, when we combine the lower limit of neutral Higgs boson mass determined from CERN e^+e^- collider LEP experiment, the lower value of Δa_μ in Eq. (1) leads to the lower bound on $h_{\mu\tau}$.

In order to calculate the contribution to a_μ from the scalar exchange, let us take the mass of the scalar to be 100 GeV which is about the value of the current LEP bounds, and assume that the mass of the pseudoscalar is large enough so that its contribution becomes negligibly small. The value of a_μ then becomes $4.65 \times 10^{-8} h_{\mu\tau}^2$. Picking up the limit for the measured value of a_μ, we can get a constraint on $h_{\mu\tau}$ which is given by $0.053 \leq h_{\tau\mu} \leq 0.09$ for $m_\phi = 100$ GeV.

Now, let us examine the lepton flavor violating processes such as $\tau \to \mu\gamma$, $\tau \to e\gamma$, $\mu \to e\gamma$, and three-body decays of τ and μ which can be induced from the FCNC couplings. A matrix element of the form,

$$i\mathcal{M} = e\overline{u}(p_2)\ i\sigma_{\mu\nu} q^\nu (A_L P_L + A_R P_R) u(p_1) \epsilon(q)^{*\mu}, \tag{6}$$

leads to the partial widths for the radiative decay modes which are given in the leading order by [7]

$$\Gamma(\tau \to e\gamma) \simeq \frac{\alpha m_\tau^5}{2^{11} 9\pi^4 m_\phi^4} (h_{\tau\tau}^2 h_{e\tau}^2 + 4h_{ee}^2 h_{e\tau}^2 + 4h_{\mu\tau}^2 h_{e\mu}^2), \tag{7}$$

$$\Gamma(\tau \to \mu\gamma) \simeq \frac{\alpha m_\tau^5}{2^{11} 9\pi^4 m_\phi^4} (h_{\tau\tau}^2 h_{\mu\tau}^2 + 4h_{e\mu}^2 h_{e\tau}^2 + 4h_{\mu\tau}^2 h_{\mu\mu}^2), \tag{8}$$

$$\Gamma(\mu \to e\gamma) \simeq \frac{\alpha m_\mu^3 m_\tau^2}{2^{13} \pi^4 m_\phi^4} (h_{\mu\tau}^2 h_{e\tau}^2), \tag{9}$$

where we have considered only tau-mediated loop contribution for the $\mu \to e\gamma$ process. The lepton flavor violating three-body decay rate of τ is given by

$$\Gamma(\tau \to l_i l_j l_k) \simeq \frac{m_\tau^5}{3072\pi^3 m_\phi^4}(h_{l_j l_k}^2 h_{l_i \tau}^2), \tag{10}$$

and a similar calculation can be done for the $\mu \to eee$ process. Contribution from the pseudoscalar exchange also exists, but is ignored since it is assumed to be heavy enough. Using the lower bound on $h_{\mu\tau}$ obtained from a_μ one can derive conservative upper bounds on the flavor changing/conserving couplings such as $(h_{e\mu}, h_{\mu\mu}, h_{e\tau}, h_{\tau\tau}, h_{ee})$ from the experimental limits of the branching ratios of $\tau \to \mu^- e^+ \mu^-$, $\tau \to \mu^- \mu^+ \mu^-$, $\mu \to e\gamma$, $\tau \to \mu\gamma$ and $\tau \to \mu^- e^+ e^-$, respectively. In addition, we can also predict the upper bounds on $Br(\tau \to e^- \mu^+ e^-)$ and $Br(\tau \to e^- e^+ e^-)$ by combining the upper bounds on $h_{e\tau}, h_{e\mu}$ and h_{ee}. In Table I, we present experimental bounds on the branching ratios of the corresponding decay processes for τ and μ and the upper bounds on the flavor changing/conserving couplings.

We note that the above numerical results crucially depends on the mass of the scalar. The bounds on the flavor changing/conserving couplings get increase as the mass of the scalar increases. When we take m_ϕ to be 1 TeV, the bound on $h_{\mu\tau}$ is given by $0.127 \lesssim h_{\mu\tau} \lesssim 0.693$. In Table II, we present the upper bounds on the flavor changing/conserving couplings and the branching ratio of lepton flavor violating three-body decays of the muon and tau lepton for $m_\phi = 1$ TeV.

In conclusion, we have examined the contribution to the anomalous magnetic moment of the muon from the exchange of the flavor changing scalar. By using the recent measurement of $(g-2)_\mu$ by the Muon $(g-2)$ Collaboration, we have obtained a bound on $h_{\mu\tau}$ for a given scalar mass. In the analysis, we assumed that the scalar is lighter than the pseudoscalar to get the positive contribution and the heavier generations have larger flavor changing couplings. Useful constraints on the other flavor changing/conserving couplings have been obtained from the lepton flavor violating decays of the muon and tau lepton, and bounds on the branching ratios of $\tau \to 3e$, $\mu \to 3e$ and $\tau \to e\mu e$ have also been predicted.

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TABLES

TABLE I. Bounds on the lepton flavor changing/conserving couplings and branching ratios generated from the lepton flavor violating decays of τ and μ for $m_\phi = 100$ GeV.

Decay process	Experimental limit	Bound
$\tau \to e\gamma$	2.7×10^{-6}	-
$\tau \to \mu\gamma$	1.1×10^{-6}	$h_{\tau\tau} \lesssim 0.113$
$\mu \to e\gamma$	1.2×10^{-11}	$h_{e\tau} \lesssim 6.14 \times 10^{-5}$
$\tau \to \mu^-\mu^-\mu^+$	1.9×10^{-6}	$h_{\mu\mu} \lesssim 0.0029$
$\tau \to \mu^-\mu^-e^+$	1.5×10^{-6}	$h_{e\mu} \lesssim 0.0026$
$\tau \to e^-\mu^-e^+$	1.7×10^{-6}	$h_{ee} \lesssim 0.0028$
$\tau \to e^-e^-e^+$	2.9×10^{-6}	$Br \lesssim 2.35 \times 10^{-12}$
$\tau \to e^-e^-\mu^+$	1.5×10^{-6}	$Br \lesssim 2.07 \times 10^{-12}$
$\mu \to e^-e^-e^+$	1.0×10^{-12}	$Br \lesssim 2.34 \times 10^{-10}$

TABLE II. Bounds on the lepton flavor changing/conserving couplings and branching ratios generated from the lepton flavor violating decays of τ and μ for $m_\phi = 1$ TeV.

Decay process	Experimental limit	Bound
$\tau \to e\gamma$	2.7×10^{-6}	-
$\tau \to \mu\gamma$	1.1×10^{-6}	-
$\mu \to e\gamma$	1.2×10^{-11}	$h_{e\tau} \lesssim 0.0026$
$\tau \to \mu^-\mu^-\mu^+$	1.9×10^{-6}	$h_{\mu\mu} \lesssim 0.122$
$\tau \to \mu^-\mu^-e^+$	1.5×10^{-6}	$h_{e\mu} \lesssim 0.108$
$\tau \to e^-\mu^-e^+$	1.7×10^{-6}	$h_{ee} \lesssim 0.115$
$\tau \to e^-e^-e^+$	2.9×10^{-6}	$Br \lesssim 7.12 \times 10^{-10}$
$\tau \to e^-e^-\mu^+$	1.5×10^{-6}	$Br \lesssim 6.28 \times 10^{-10}$
$\mu \to e^-e^-e^+$	1.0×10^{-12}	$Br \lesssim 7.10 \times 10^{-8}$